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Realizing the potential of integrated irrigation and drainage water management for meeting crop water requirements in semi-arid and arid areas

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Abstract. *In situ* use of ground water by plants is one option being considered to reduce discharge of subsurface drainage water from irrigated agriculture. Laboratory, lysimeter, and field studies have demonstrated that crops can use significant quantities of water from shallow ground water. However, most studies lack the data needed to include the crop water use into an integrated irrigation and drainage water management system. This paper describes previous studies which demonstrated the potential use of ground water to support plant growth and the associated limitations. Included are results from three field studies which demonstrated some of the management techniques needed to develop an integrated system. The field studies demonstrated that approximately 40 to 45% of the water requirement for cotton can be derived from shallow saline ground water. That regulation of the outflow will result in increasing use. Implementation of integrated management of irrigation and subsurface drainage systems is a viable and sustainable alternative in the management of subsurface drainage water from arid and semi-arid areas only if soil salinity can be managed and if the system is profitable.

Key words: cotton, drainage, irrigation, salinity, shallow groundwater, tomato

Introduction

The solution to several vexing water management problems can be aided by integrating the design and management of irrigation and subsurface drainage systems. In arid and semi-arid areas of the western United States of America, water supply is becoming a critical issue. There is increasing pressure on agriculture to relinquish a portion of its supply to meet the demands of an increasing urban population for municipal and industrial uses and for environmental enhancement. In California, USA, nearly 85% of the developed water supply is used by agriculture for irrigation on roughly 3.6 million ha of land. There are approximately 3.3×10^7 ML used for irrigation and small improvements in irrigation efficiency will have a significant impact on the availability of water for other uses.

Environmental quality issues are significant in relation to irrigated agriculture. Removing water from rivers and streams has resulted in a loss of fisheries and other water related recreational benefits. In addition to the loss of water, there are negative impacts associated with the discharge of subsurface drainage water containing salts and trace elements to rivers and streams. Improved management of irrigation and drainage systems will have a two fold effect. Less water will be required to maintain production. The conserved water could then be used for additional water for environmental purposes such as in-stream uses. Reduced drainage flows will result in less transport of salt and trace elements to surface water, thereby improving over all water quality.

Typically, irrigation and drainage systems have been designed and operated independently. Design of irrigation projects in arid and semi-arid areas typically proceeds from the design of the irrigation system to the design of the drainage system. Sometimes there is the foresight, that a drainage system is required to maintain a salt balance in the irrigated area, so provisions are made to ensure an adequate drainage system should it be needed. Frequently, the irrigation system is installed and operated and the drainage system follows in response to water logging and salinity problems.

Historically, the drainage system is designed on the premise that it is free flowing and that all the deep percolation losses from the irrigation system and any lateral inflows collected by the system are discharged. One objective of the drainage design is to maintain the mid-point water table position between drains at a depth greater that 1.1 m to control capillary upflow and salinity (US Department of Interior 1993). Using this criteria has resulted in over drainage and a waste of water (Doering et al. 1982) which could be saved or used to meet the crop water requirement. This is particularly true in areas which contain little or no native soil salinity. In semi-arid areas the average rainfall is often adequate to provide the leaching required to manage soil salinity. This may not be the case when soils contain high levels of naturally occurring salinity and additional leaching is required. In the long run, if rainfall is adequate to maintain "salt balance" then it will also provide the leaching needed to reclaim irrigated soil.

For the integrated design and management of irrigation and subsurface drainage systems to be effective and practical the following questions need to be answered: (1) Will crops use water from shallow ground water; (2) What affects the amount used; (3) How much water is used; (4) What is the impact on soil salinity; (5) What is the impact on yield; (6) How do you manage the irrigation and drainage systems to maximize water use; (7) Which irrigation system is most effective; (8) What type of design is needed for the drainage system; (9) How sustainable is the system; (10) What are the economic advantages and disadvantages of this system?

The objective of this paper is to review previous research and summarize field studies done by the authors related to crop water use from shallow ground water, factors affecting crop use, volume of water taken from ground water, impacts on yields, and combined management of irrigation and drainage systems.

Crop water use from shallow ground water

There is extensive literature quantifying crop water use from shallow ground water in both humid and irrigated areas throughout the world. Crop water use from water tables in irrigated areas is of primary interest in this study. Water control systems such as those used in humid areas differ significantly from the concept being discussed here.

The principal design objective in humid areas is to prevent waterlogging and not manage salinity. Drainage systems in humid areas are installed at shallower depths and with closer spacings than typically found in irrigated agriculture (Ayars 1996). The land being drained is nearly flat and controlling the depth to the water table is possible over a large area using a single structure at the drainage outlet which is generally not the case in arid areas. Water can be pumped into these systems to provide sub-irrigation potential (Fouss et al. 1990). Deep percolation from rain water is the primary source of water being controlled by the system unless water is diverted from a stream or other source into the drainage system (Skaggs 1980).

The Maas-Hoffman (1977) threshold for plant salt tolerance has generally been used to establish the potential for plant use of saline water without any adverse effects on yield. It was assumed that any salinity values in excess of the threshold resulted in a yield decrease. It was theorized by van Schilfgaarde et al. (1974) that plants could use water at a significantly higher salinity than previously thought possible before deleterious effects on yield were observed. This was true after plants were well established. Hutmacher et al. (1996) demonstrated that cotton could use saline ground water, 15–20 dS m^{-1}, approximately equal to twice the Maas-Hoffman threshold, at the same rate as low-salinity water (< 0.4 dS m^{-1}).

Field and lysimeter studies have quantified crop use from shallow ground water for a wide range of crops. In a semi-arid area with non-saline ground water, Benz et al. (1978) found that alfalfa, sugar beet, and corn all used significant amounts of water from a shallow (< 1m) water table. Based on this research, Doering et al. (1982) proposed a shallow drainage design concept to increase crop water use from shallow ground water for semi-arid areas with good quality ground water by reducing the depth of drain lateral installation. Implementation of this concept would reduce drainage discharge and applied irrigation water and result in improved irrigation efficiency thus saving water and energy (Benz et al. 1987). The shallow drainage concept was originally proposed in an area which does not contain significant amounts of soil salinity or saline ground water.

Using column lysimeters Namken et al. (1969) determined that cotton could get up to 60% of its water requirement from a saline water table (1.6 dS m^{-1}) at a depth of 0.9 m. This is consistent with the data of Wallender et al. (1979), who found similar ground water use by cotton from saline water (5–7 dS m^{-1}) at a depth of up to 2 m. Hutmacher et al. (1996) found that cotton water uptake from a depth of 1.1 m was not affected by ground water salinity until the salinity was in excess of 15 dS m^{-1}. Grimes & Henderson (1984) determined in field studies that crop water use for cotton and alfalfa from shallow saline (5–26 dS m^{-1}) ground water was a function of both depth to ground water and salinity of ground water. They determined that percentage uptake by alfalfa was in the range of 14 to 45% of the crop water use depending on the equation used to calculate reference evapotranspiration (ET_o). Water use from shallow ground water by cotton ranged from 27 to 60% again depending on the calculation of ET_o. Grimes & Henderson (1984) determined upflow as a difference in the water balance equation which means that the value was dependent on the calculation of ET_o and the crop coefficient used in the calculation of crop water use.

Kruse et al. (1985), using lysimeters, determined that corn grown in the presence of saline ground water (6 dS m^{-1}) obtained approximately 55% of its water requirement when that water table was within 0.6 m of the ground surface. They found that increasing the depth to ground water had a larger effect on crop uptake than did the increase in ground water salinity. The corn was irrigated with a low salinity water typical of the Colorado River at Grand Junction, Colorado.

Using lysimeters, Meyer et al. (1996) determined that alfalfa would use from 13 to 55% of its crop requirement from shallow ground water depending on soil type and ground water salinity when the water table was maintained at a depth of 0.6 m. The percentage contribution was lower for finer textured soil and higher ground water salinity. With an EC of 1.6 dS m^{-1} in the ground water, the percentage contribution was in the range of 22 to 55%. When the ground water salinity was increased to 16 dS m^{-1} the percentage contribution reduced to 13 to 25%.

One weakness in most of the aforementioned studies is the lack of information needed to properly devise an irrigation schedule containing both the timing and depth of application of irrigation water. These studies have quantified use from ground water over the season but not necessarily as a function of parameters such as plant growth, days after planting, and growing degree days which can be used in a scheduling program.

Factors affecting crop water use from shallow ground water

Crop salt tolerance will have a major effect on the potential of the crop to beneficially use shallow ground water. The salt tolerance data presented by Maas (1990) are starting points to determine the potential contribution based on the salinity of the ground water. Hutmacher et al. (1996) demonstrated that plants could use water with salinity nearly twice the Maas-Hoffman threshold at the same rate as for water less than the threshold. When that level was exceeded the crop water use reduced significantly but was not stopped. The work done by Meyer et al. (1996) on alfalfa demonstrated maximum potential with a ground water salinity of 1.6 dS m^{-1} and a 50% drop when the ground water salinity was increased 10 fold. The Maas-Hoffman threshold value for alfalfa is 2dS m^{-1}.

The crop age influences potential ground water use in two ways. First, it has been demonstrated that plants tend to be more salt sensitive during early growth stages than in later growth stages (Maas 1986). This suggests that as a plant matures it would have the potential to extract poorer quality from ground water than might be indicated by is salinity tolerance classification given by the Maas-Hoffman (1977) threshold values.

Roots have to be in the vicinity of the water table to maximize the uptake potential. The extent of rooting is the second factor which will be affected by crop age. The potential for crop water use increases as the root system develops in volume and length during growth. Borg & Grimes (1986) characterized the development of the root system based on the plant growth in relation to days to maturity. In arid areas, plant and root development can be estimated reasonably well and used to characterize the changes in volume of stored soil water and the position of the root system in relation to the water table. This information is needed to develop an irrigation scheduling methodology which includes crop water use from shallow ground water.

Water quality (both irrigation and ground water) and irrigation management will have a significant effect on the potential for crop water use from shallow ground water. Plants will selectively extract water from the portion of the root zone having the highest potential either due to low salinity in the soil water or high water content. There will be little extraction from the ground water until the soil water content is reduced or becomes more saline. Water uptake from the water table has to be induced by reducing the stored water in the root zone and then irrigating in a fashion which requires extraction from the water table to meet the crop water requirement. By extending the irrigation interval it is possible to achieve this effect. Using an indicator such as leaf water potential (LWP) for scheduling has successfully extended the irrigation interval and increased shallow water table contributions to meet the crops total water requirements (Kite & Hanson 1984).

Irrigation method also affects the potential extraction of ground water for meeting crop water requirements. Surface irrigation methods are limited in the minimum possible application depth and these generally fall in the range of 50 to 100 mm. Maximum ground water use occurs at the end of the irrigation interval just prior to the next irrigation. This is particularly true in the early growth stage when the root system is still small. The most effective method to increase shallow ground water use with surface irrigation will be to extend the irrigation interval as the crop grows with alternative scheduling methods and to eliminate the final irrigation before harvest.

Pressurized systems such as sprinkler and drip allow automated operation of the system with good control on the depth of application. With drip irrigation the irrigation interval is set for daily or near daily applications. When this is the case the application depth has to be determined by underestimating the previous days crop water use. By routine deficit irrigating, it is possible to induce extraction from the stored soil water and then from the ground water. If water is applied to meet the previous days Et_c, no potential is established for water extraction from other sources, such as stored soil water and ground water. Irrigation should begin only after the soil water has been reduced. Sprinkler systems are ideally suited for use in maximizing potential crop water use from ground water because the depth of application can be controlled with greater precision than surface systems such as furrow and flood.

Dugas et al. (1990) determined the effect of soil type on soybean crop water use from ground water at a depth of 1.0 m. They demonstrated that use of water from shallow ground water was reduced in a soil with a high percentage of clay and a compacted layer compared to a less dense soil without a compacted layer. The reduced hydraulic conductivity in the compacted soil and the reduced root length density in the zone above the water table were responsible for the reduction in water use. They also determined that extraction from ground water was increased as soil water content was reduced in the upper portion of the root zone. This increased hydraulic gradients and increased the potential for water to move into the root zone. The majority of the crop water use came late in the season as a result of the reduction in soil water. This was also demonstrated by Wallender et al. (1979) in a field study on cotton.

Use of shallow ground water as a supplemental water supply in irrigated agriculture is sustainable if several conditions can be met. The source of water supplying the ground water will be a major factor in determining the sustainability as will the ground water quality. If the ground water is the result of poor irrigation practices, the volume available is limited if irrigation is improved and deep percolation reduced. Lateral inflows are potential sources of water but these need to be quantified to determine the volume and extent of the supply and whether it is a result of local or regional poor irrigation practices or rainfall.

The salinity of the ground water will determine whether and how much water will be extracted by the plant and the effect on soil salinity. Crop use transports both salt and water up into the profile but the salt remains after the water is extracted. This leads to a gradual salinization of the soil which eventually eliminates production if not properly managed. Leaching of salts is the required management and this requires disposal of drainage water. If disposal of drainage water is not possible then lateral flow from the area or percolation through the impeding layer will be required to discharge salt. There is little incentive to implement management systems which increase shallow ground water use if yields are not maintained, production costs reduced, and profits increased.

Managing both the irrigation and drainage systems

Maximizing the potential crop water use will require the integrated management of the irrigation and drainage systems. For the combined approach to work, the crop has to be well established and growing vigorously. At germination and early growth there is essentially no water use from the ground water. After the plant is established the irrigation system is managed to extend the root system and dry down the upper part of the root zone. This is accomplished by extending the irrigation interval and reducing the applied water. By under-irrigating the crop, the plant will seek alternate water sources and begin to use more water from deeper in the soil profile and from shallow ground water in preference to reducing soil water in the upper portions of the root zone.

Leaf water potential (LWP) has been used effectively for irrigation timing in cotton (Kite & Hanson 1984). This technique integrates both the osmotic and matric potentials experienced by the plant. Grimes & Yamada (1982) established threshold values to initiate irrigation of cotton based on plant development. Similar values are not available for other crops which limits the utility of this technique.

After establishing the time of irrigation, the depth of application is determined based on soil water content by methods such as gravimetric sampling, measurement with a neutron probe, or another soil water sensing device. Water balance calculations to determine both the timing and depth of application are generally not possible in shallow ground water systems since the ground water contribution to crop water use is unknown. Ayars & Hutmacher (1994) modified a cotton crop coefficient to account for the ground water contribution to evapotranspiration as a function of ground water salinity and depth to ground water. Application of this technique permits water balance determination of a cotton irrigation schedule which includes both depth and timing.

Part of the integrated management requires maintenance of the water table at a depth which is readily available to the plant later in the growing season. This is accomplished by restricting the flow in drains or checking the system outlet to maintain the water table at a higher depth than was used in design. This is similar to the technique used for sub-irrigation in humid areas (Fouss et al. 1990). However, this is difficult in arid areas because often the drain configuration is such that the laterals run parallel to the surface slope and raising the water table depth at the tail end of the field will have little impact on the water table at the head end of the field. In these situations, in-field control on the laterals is needed to distribute the ground water over a larger area.

For new systems, the drainage laterals and mains should be installed such that the laterals are placed approximately perpendicular to the field surface slope and the collector submain is installed such that the flow and depth can be controlled at several points along its length. Placing control structures at the edge of the field will minimize obstructions in the field.

Designing the system based on a smaller mid-point water table depth criterion will give potential to increase shallow ground water uptake and decrease drainage (Doering et al. 1982). Maximum effect can be achieved when the new system design is coupled with outlet control. Reducing depth of installation from 2.1 to 1.5 m with a proportional reduction in drain spacing will result in the water table being closer to the soil surface throughout the growing season. Also, the shallower depth of drains means the volume of water stored between 1.5 and 2.1 m is available for plant use. When drains are placed at a depth of 2.1 m the water table is drawn down quickly and the water is not available for plant use. Shalhevet (1994) stated that the critical design aspect of drainage design was maintenance of aeration status plus providing adequate leaching. Both of these criteria can be met with the proposed modifications in design and management of subsurface drainage systems.

An alternative technique for reducing drainage discharge has been proposed by Manguerra & Garcia (1997) using drains installed at a depth of 2.1 m. They proposed a series of alternating drainage and no drainage cycles. In their proposal, after a leaching event the water table is lowered to the level of the drains which are closed and no drainage is permitted until the water table rises to a predetermined depth or until soil salinity levels are reached which damage yields. At this time the drains are opened and drainage and leaching occur and the process begins again. For this procedure to be effective the drainage system needs to be configured to distribute the water table as uniformly as possible under the field.

Also, detailed monitoring of the soil salinity and yield will be required during operation to determine if yield losses or depth to water table will be the dominant operating condition.

Case studies

Field studies done in the San Joaquin Valley of California have contributed to the understanding and development of practices needed for the integrated management of irrigation and drainage systems in arid irrigated conditions. These study results will be used to demonstrate the implementation of the concepts needed for integrated management of irrigation and drainage systems.

Murrieta farms

This study was located on the westside of the San Joaquin Valley of California at Murrieta farms. It is discussed in detail in other publications (Ayars and Schoneman 1986; Ayars et al. 1986). A summary of the data and results from those publications are included here to demonstrate previously discussed concepts. Data are reported in this paper from four plots containing subsurface drains that were furrow irrigated each year of the study (1982–1984).

The average electrical conductivity (EC) of the ground water was 10 dS m^{-1} and the EC of the irrigation water was 0.2 dS m^{-1}. Reference evapotranspiration (Et_o) was calculated hourly using the Penman equation with daily Et_o being equal to the sum of the hourly values. Cotton *(Gossypium hirsutum* L. cv Acala SJ-2) was grown each year of the study. Leaf water potential (LWP) was used to schedule the time of irrigation in all years. A sustained LWP of –1.8 MPa measured on the first fully expanded leaf at mid-day was used to initiate irrigation (Grimes & El-Zik 1982).

Irrigation water was measured with water meters. Stored soil water was calculated from neutron data taken before and after irrigation with adjustments to account for crop water use during the interval between measurements. Runoff and deep percolation components were calculated as difference between applied and stored water. Change in soil water storage was calculated from neutron data taken at the beginning and end of the season. An estimate of crop evapotranspiration (Et_c) was calculated from cotton yield with the production function developed by Grimes & Dickens (1977). The calculated value of ground water contribution depends the method used to calculate crop evapotranspiration. The options were either Et_c based on the crop production function or Et_o multiplied by a crop coefficient. A production function was used for this analysis and it had the lowest yield per unit of Et, ensuring that the estimates were conservative. Upward flow was the contribution of water to crop needs from the water table. This was calculated as the difference between the Et_c estimated with the production function and the sum of the soil water depletion and the infiltrated irrigation water, less deep percolation.

During three years of the operation of this project the contribution of ground water to crop water use varied from 0 to 37%. Comparing the water use between 1982 and 1984, the total water extracted from ground water, from all plots, was higher in 1982 than in 1984 as a result of an extra irrigation in 1984 which increased the total stored water and reduced potential uptake. These data are shown in Figure 1. The pattern across the plots shows that as the stored water from irrigation (SIW) increases, the total usage from ground water (WT) decreases (increasing negative number). This pattern is also true for the soil water depletion (SWD). This emphasizes the importance of extending the irrigation interval and possibly timing of the last irrigation of the season.

The water table response to irrigation is also an important consideration. Traditional design procedure (US Department of Interior 1993) indicates that the depth to the water table decreases over the irrigation season with the mid-point depth being closest to the soil surface at the end of the irrigation season. This was not the case at this site. The minimum depth to the water table occurred after the first irrigation and declined for the remainder of the irrigation season (Figure 2), as was predicted by Ayars & McWhorter (1985). This works to the benefit of the proposed management system. If the flow from the drainage system is restricted, the water table will remain higher longer and increase the opportunity time for plant use from ground water. Aeration should not be a problem at the beginning of the growing season since the root system is not completely developed.

In a companion study on this field, cotton was drip irrigated with saline water with an EC of 8 dS m^{-1} using surface drip irrigation (Ayars et al. 1986) with two irrigation frequencies. Irrigation was either daily, applying a depth equal to the previous day Et_c, or after 25 mm of accumulated Et_c,

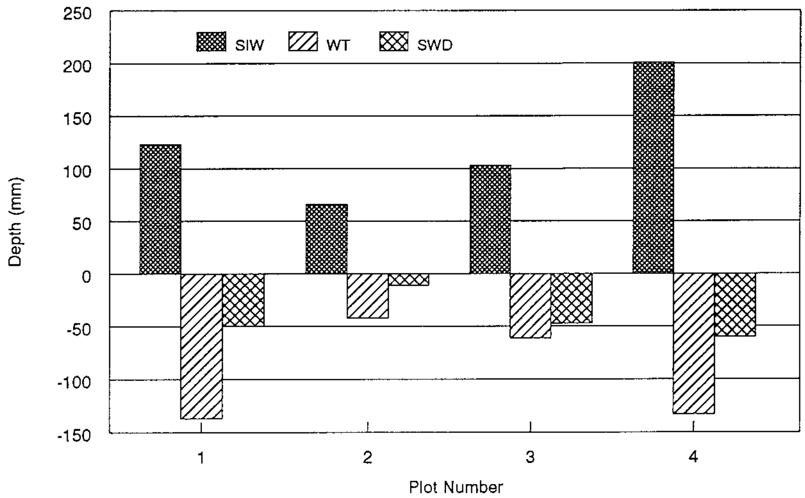

Figure 1. Differences in the water table contribution to evapotranspiration between 1982 and 1984 compared to stored irrigation water (SIW) between 1982 and 1984.

which was then applied. During peak ET_o irrigation was approximately every two to three days. The depth of application ranged from 100% to 130% of Et_c. Ground water contribution was estimated at 104 mm when cotton was irrigated daily compared to 311 mm when cotton was irrigated every 2 to 3 days.

The water balance data (not shown) (Ayars & Schoneman 1986) showed that large quantities of a poor quality shallow ground water can be used by cotton without any yield loss. In 1982, an average of 167 mm of shallow perched water was used for crop production on the 40 ha test area. This is equal to 66,800 m^3 which did not enter the drainage system. Plant usage from ground water was estimated to be 43 mm in 1983 and 74 mm in 1984.

The soil salinity was monitored in response to the irrigation management. The changes in the EC in the saturated soil water extract are given in Table 1 for plot 2 on the Murrieta project, for the time period from spring 1983 to fall of 1984. The data show an increase in soil salinity in the soil profile over the growing season in each year. The salinity in the 0 to 0.3 m depth of the profile is controlled from year to year by pre-plant leaching while the salinity in the remainder of the profile has increased. Additional leaching is required to reduce the salinity in the lower portion of the profile. This is often accomplished with furrow irrigation during the first seasonal irrigation. However, the EC values in Table 1 would not create a problem for the germination and growth of cotton.

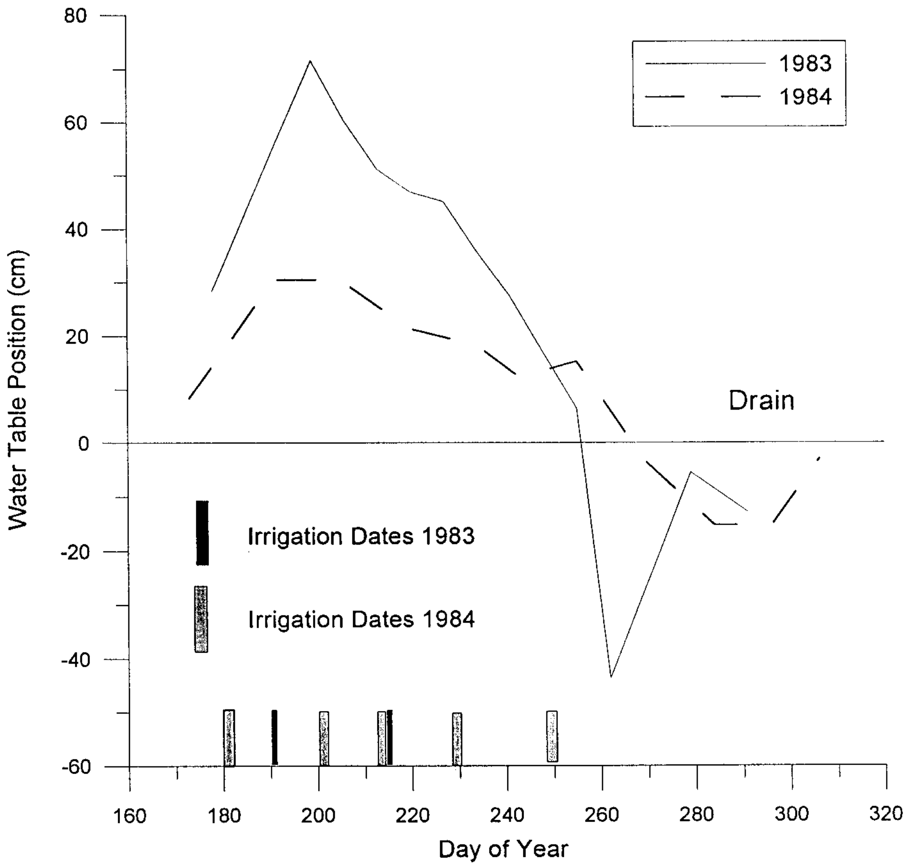

Figure 2. Mid-point water tabe response to irrigation under plot 3 at Murrite site in 1983 and 1984.

Table 1. Electrical conductivity in saturated soil extracts from plot 2 of the Murrieta water management project as a function of depth in 1983 and 1984.

	Electrical conductivity (dS m^{-1})			
Depth (m)	Spring 1983	Fall 1983	Spring 1984	Fall 1984
0–0.3	1.2	4.1	2.3	1.4
0.3–0.6	2.5	7.8	4.3	11.2
0.6–0.9	5.5	8.8	7.3	10.9
0.9–1.2	8.2	7.7	15.1	9.6

Britz farms

The site selected for the research on managing subsurface drip irrigation(SDI) in the presence of shallow ground water was located on one of the Britz ranches south of Mendota, California in what has been identified as the drainage problem area (San Joaquin Valley Drainage Program 1990). Two quarter sections (Sections 36 and 1) were used for the project. The details of the project are discussed in (Ayars et al. 1992). Procedures are summarized below for the benefit of the reader.

The drip lateral spacing used in section 36 was 1.68 m which corresponded to the conventional bed size used for tomatoes. Subsurface drip laterals were shanked in the middle of each bed at a depth of approximately 40 ± 5 cm below the bed surface. The lateral spacing used in section 1 was 2 m which corresponded to placing the drip tubing between every other row of cotton. The laterals were shanked to a depth of 40 ± 5 cm below the bottom of the furrow.

A furrow irrigated plot adjacent to the SDI plots was used for plant response and yield comparisons. The furrow lengths were 396 m and irrigation water was supplied to alternate furrows by gated pipe. Irrigation scheduling was the responsibility of the cooperator.

Cotton (*Gossypium hirusutum* L. var. MAXXA) was planted on day of the year (DOY) 103, drip irrigation began on DOY 162 and ended on DOY 237. Irrigation was scheduled after 4 mm of ET_c had accumulated and a total of approximately 4 mm was applied to each irrigation. Furrow irrigation occurred on DOY 164, 217, and 233 with 140, 140 and 56 mm being applied respectively. Pre-plant irrigation of 210 mm was applied to all plots by furrow irrigation on DOY 1. Irrigation water was supplied by the Westlands Water District and was a good quality (EC = 0.4 dS m^{-1}).

A grid of observation wells made of 38 mm diameter PVC tubing was used to monitor the groundwater depth and quality in all plots. The depth to the water table was measured every two weeks and the shallow groundwater was sampled at the time of measurement of water depth.

Leaf water potential (LWP) was measured three times a week in each plot using a pressure chamber. The most recently fully expanded leaf was covered with a polyethylene bag, excised from the plant, and stored in a moist dark container prior to measurement. Four leaves were measured in each plot. All measurements were made within 30 minutes of excision of the leaves. Biomass was determined on DOY 253 for use in estimating ET_c. All cotton plants in 6.1 m row length, in three replications, were cut level with the soil surface and weighed to determine the fresh weight. A total dry matter to fresh weight ratio was used to determine the average total dry matter. Cotton yield was determined by machine harvesting from each plot until a module was filled. The harvested area was measured and used with the gin records for lint weight for each module to determine the lint yield per ha.

Scheduling subsurface drip irrigation

The modified cotton crop coefficient developed by Ayars & Hutmacher (1994) was used to schedule the operation of a subsurface drip irrigation system (SDI). Results from two drip plots in section 1 designated A and B will be used in this discussion.

Lateral lengths were 396 m and 198 m in Plot A and Plot B, respectively. The pressure was maintained by pressure reducing valves installed on each treatment and the operating pressures were 69 and 104 kPa in Plots A and B, respectively. The tubing discharge rate was 0.57 and 0.76 L/min for each 30 m of lateral in Plot A and B, respectively.

Crop evapotranspiration (Et_c) was calculated by multiplying the evaporation from an on-site evaporation pan (E_{pan}) by a pan coefficient (k_p) and a crop coefficient (k_{cbgw}). The resulting expression for crop evapotranspiration is $Et_c = k_{cbgw}{}^*k_p{}^*E_{pan}$. The crop coefficient was for a depth to shallow groundwater of 2 m and an electrical conductivity of 7.7 dS m^{-1} (Ayars & Hutmacher 1994). The evaporation pan coefficient was determined by comparing the measured on-site pan evaporation to a reference Et_o computed using climatic data collected by a weather station located approximately 6 km from the site.

Accumulated growing degree days (GDD) from the field site were used to match the growth stage in the field to the modified crop coefficient for use in calculating the irrigation schedule. Temperature measurements were taken from the weather station located 6 km from the site.

The initial water table depth in the field under the plots ranged from 1.2 to 1.4 m and the EC of the groundwater ranged from 4 to 5 dS m^{-1}. The crop coefficients used in this experiment are given in Figure 3 along with the basal crop coefficient used in the development of the modified coefficient and curves for two depths to groundwater and several groundwater qualities at 1.2 m depth to water.

The cumulative Et_c, calculated using the base coefficient, is given in Figure 4 along with the cumulative Et_c calculated with crop coefficients for groundwater contribution from a water table at a depth of 1.2 m and 2 m and salinity of 7.7 dS m^{-1} or less. The cumulative applied water for each of the SDI plots is also shown in Figure 4.

The management goal was for the applied irrigation water to equal the cumulative Et_c based on the adjusted crop coefficient. The cumulative irrigation data show that plot A was consistently under-irrigated as a result of the operational characteristics of the system. The low operating pressure needed

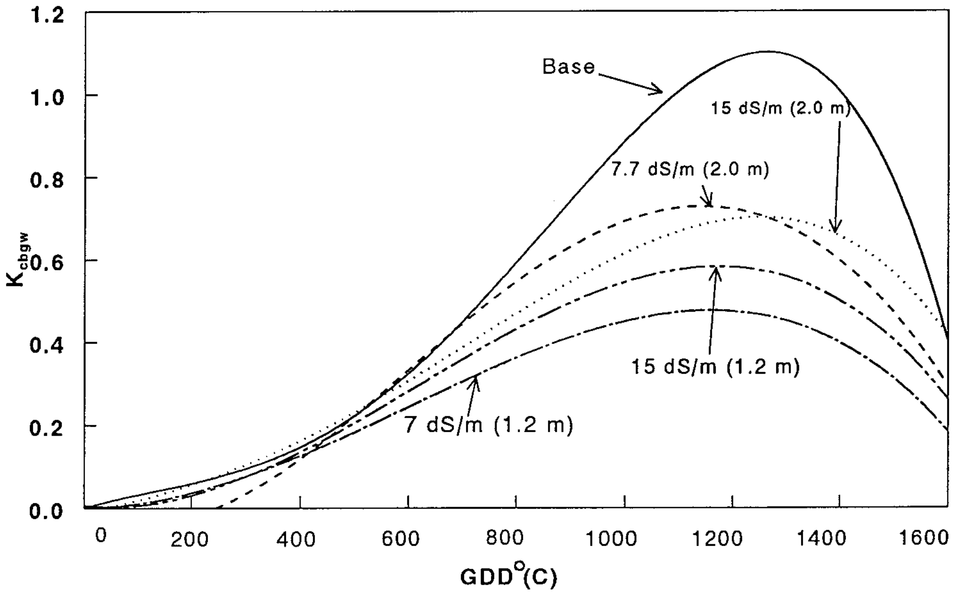

Figure 3. Modified cotton crop coefficients used for irrigation scheduling of cotton in the presence of shallow ground water.

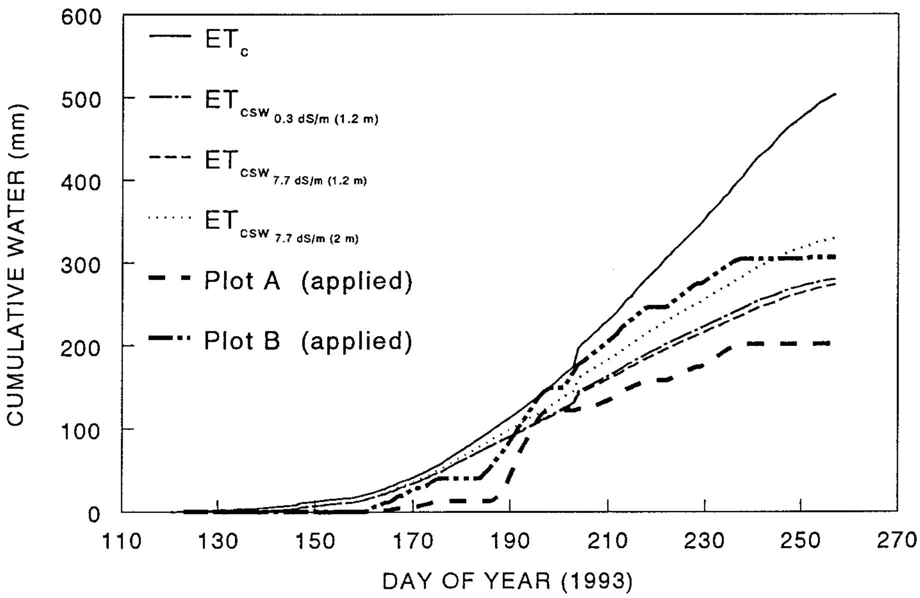

Figure 4. Cumulative applied irrigation water and calculated cotton evapotranspiration.

for this system was difficult to maintain and occasionally the valve did not operate. This resulted in the system, at times, not irrigating when it should have.

The cumulative applied water in Plot B followed the cumulative Et_c calculated using the crop coefficient (K_{cbgw}) derived using data for a 2m deep water table and a groundwater salinity of 7.7 dS m^{-1}. For the time period DOY 120 to DOY 235, the Et_c calculated with the base coefficient (GW = 0) was 400 mm while the Et_{csw} (evapotranspiration from stored soil water) calculated with the modified coefficient was 330 mm. The cumulative irrigation in Plot B was 307 mm for this same time period. The difference in the calculated base Et_c and the Et_{csw} calculated using the modified basal crop coefficient (K_{cbgw}) reflects the groundwater contribution to crop water use. Over the interval DOY 120 to DOY 235, approximately 25% of the crop water use is estimated to have been taken from shallow groundwater. This highlights the fact that the proposed modified basal coefficient (K_{cbgw}) purposely underestimates Et_c in order to induce shallow groundwater use by delaying irrigation. The unmodified base coefficient was used to estimate the actual Et_c. Crop development was monitored in each plot and no differences were observed in plant height and canopy development.

The LWP data for Plots A and B and the furrow irrigated comparison plot are given in Figure 5. The furrow plot was slightly more stressed than the drip plots but none of the plots had excessive stress. In the San Joaquin Valley, a stress value of –1.8 MPa is considered a level requiring irrigation for cotton. This level was not reached until after irrigation was stopped on all plots.

An independent estimate of Et_c was made using the plant biomass data on DOY 253. Using the equation $TDM = -2.94 + 0.03^{*}ET_c$, with TDM equal to total dry matter in T ha^{-1} and Et_c in mm (Davis 1983), the Et_c estimate from planting to day 253 was 600 mm. This compares to an estimated Et_cvalue of 510 mm calculated using the basal crop coefficient.

The lint cotton yield was 2300 kg ha^{-1} in Plot A, 1800 kg ha^{-1} in Plot B and 1500 kg ha^{-1} in the furrow plot. While the yield in both drip plots exceeded the yield in the furrow irrigated plots, the yields in all plots were acceptable or higher when compared to the average of approximately 1500 kg ha^{-1} for this area.

The water table response is shown in Figure 6 for the area under the drip plots and under the furrow plot. There was nearly a one meter decline in the water table under each of the plot areas. The depth to water was such that the crop could easily take advantage of the shallow groundwater to meet water requirements.

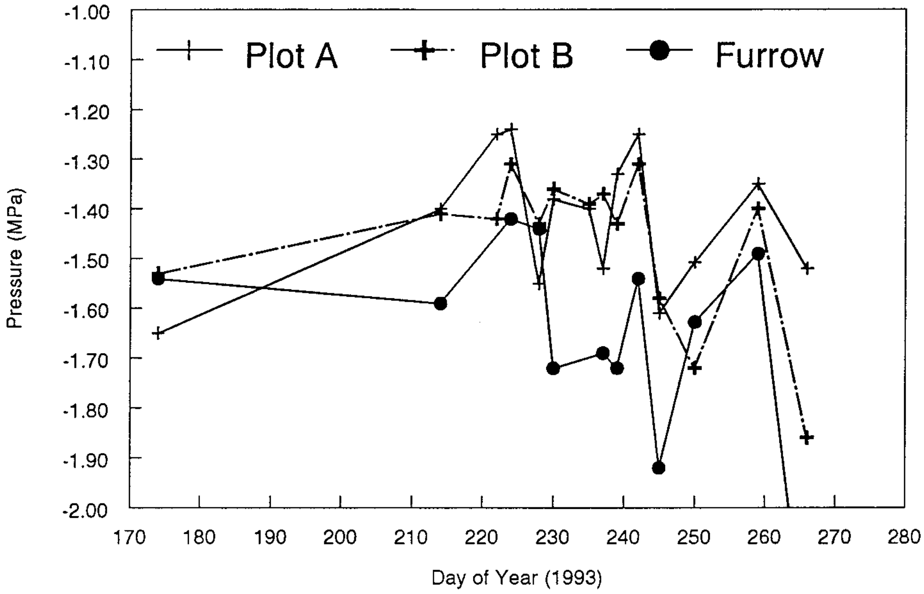

Figure 5. Leaf water potential for subsurface drip and furrow irrigated cotton plots in 1993 at Britz farms.

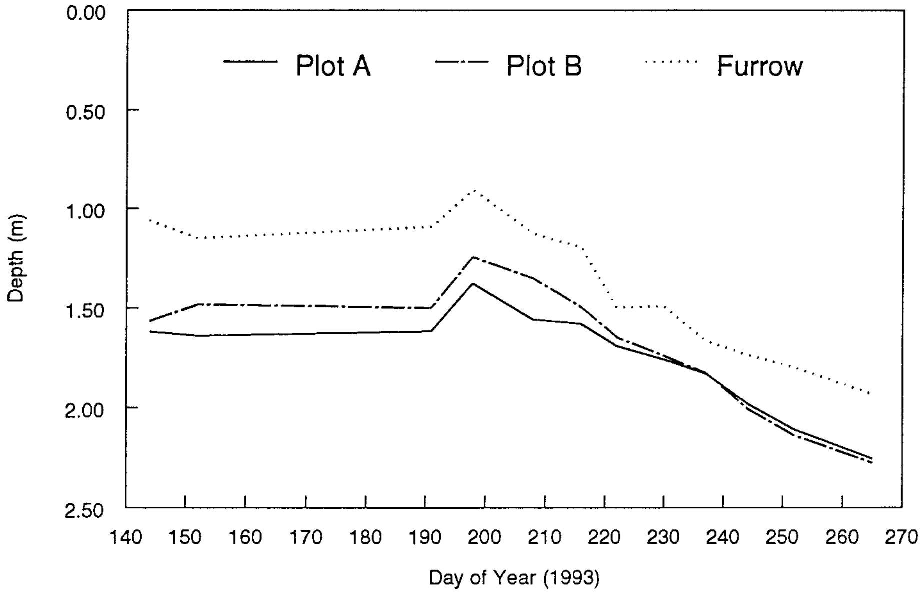

Figure 6. The water table response under drip and furrow irrigated plots at Britz farms.

Cilker farms

Drain system control

The objectives of the drain control project were to reduce the volume of drain water by using shallow groundwater to meet a portion of the crop water requirement and possibly reducing depth of applications for each irrigation. A subsurface drain system of corrugated plastic tubing, which had previously been installed on 65 ha of land located in the Broadview Water District, was used for this research. The system layout is given in Figure 7, and details of the project can be found in (Ayars 1996). Three areas in the field were identified to characterize vegetative response to the water table depth, labeled shallow (S), medium (M), and deep (D). The drain laterals were installed on grade from west to east with the outlet on the east side of the field. The tomato rows were in a north-south orientation, perpendicular to the drain laterals. The individual sites were located such that the shallow site was on the east side of the field, the deep site on the west side and the medium site located between the two. LWP was determined two to three times a week at each of these.

The water table response to valve operation is shown in Figure 8 for the period between the irrigations on 4/17/94 and 5/25/94. In Figure 8, the control structures are located at 670 m on the x-axis. The soil surface is shown as the upper surface grid and the water table as the lower surface grid in Figure 8. After the valves were closed on each lateral, the water table rose to within a meter of the soil surface. The valves were opened and the water level receded to approximately 2 m below the soil surface (Figure 8). The valves were opened because the ranch manager wanted to dry the soil profile in preparation for harvest.

The shallow area close to the control structures had a water table fluctuation from 1.5 to 2.2 m below the soil surface. The medium depth area had a water table depth of 1.8 to 2.6 m during the experimental period and the deep area had a water table depth of 2.2 to 2.6 m during the project.

The plant and yield responses were measured in three areas in the field. The LWP is given in Figure 9 for plants growing in each experimental area. The data show that the plants were progressively more stressed as the initial depth to the water table increased. A potential of –0.9 to –1.1 MPa is considered a minimal stress level for tomatoes. This level of stress did not occur in the shallow water table (S) area and was only slightly exceeded in the medium water table (M) depth areas. During the entire time of measurement, the plants in the deep water table (D) area were stressed at a much higher level than in the other areas.

The EC of the shallow groundwater ranged from 3 to 8 dS m^{-1} which is usable by a tomato crop. Hutmacher & Ayars (1991) demonstrated that tomatoes could extract up to 45% of the water requirement from 5 dS m^{-1}

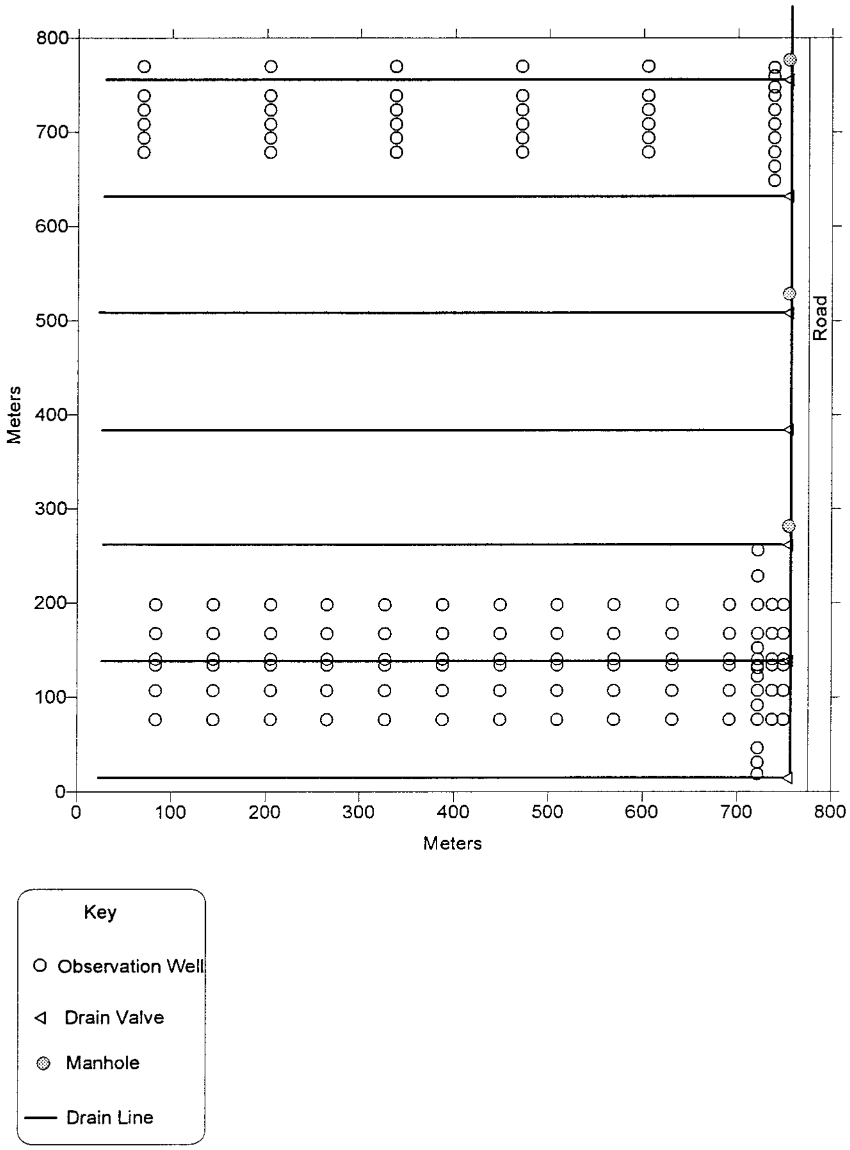

Figure 7. Drain system layout showing installation of observation wells, drain valves, and manholes at Cilker farms.

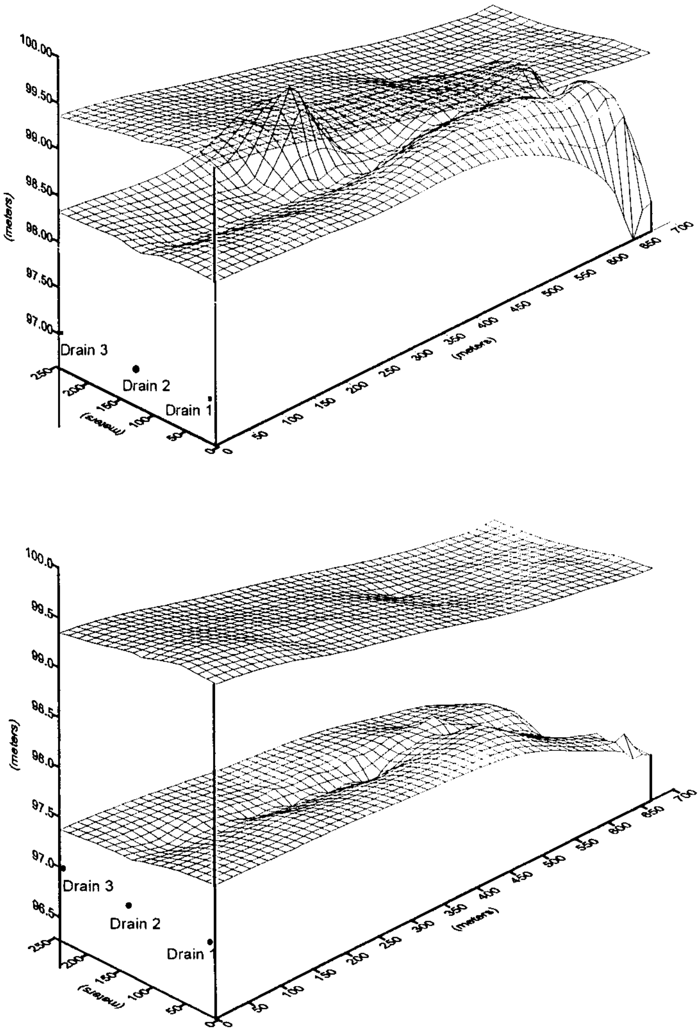

Figure 8. Water table response to drain valve operation under a furrow irrigated tomato field between 4/17/94 and 5/25/94.

water when the water table was within 1.2 m of the soil surface. The improved plant vigor and reduced stress levels in the shallow and medium depth areas indicated that the crop was using shallow groundwater.

Maintaining the shallow groundwater reduced the crop irrigation water requirement by 141 mm. A companion field which did not have water table control required 829 mm of irrigation and the test field needed only 688 mm. This resulted in a savings of 6.5×10^5 m^3 of water. Water application data

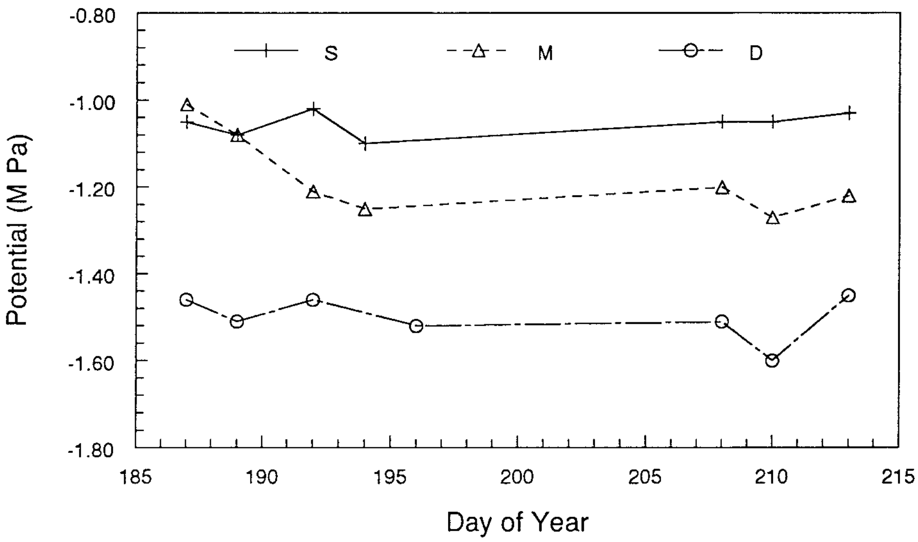

Figure 9. Tomato leaf water potential with shallow (S), medium (M), deep (D) water table depths.

were available from the irrigation district and yield data for each field were available from the cooperator. There was no difference in yield between the fields.

Discussion

Crop water use from shallow ground water

Crop water use from shallow ground water has been well documented for crops growing in arid, semi-arid, and humid areas in throughout the United States and in other countries throughout the world. The total water use has been developed using both field and lysimeter studies. Crops investigated include cotton, sugar beet, alfalfa (both seed and forage), barley, tomato, and corn. Field studies have generally quantified the crop water use based on water balance studies with upflow from the water table being the remainder in the equation. The total water use is then dependent on the accuracy of the measured values of applied water, changes in stored soil water, and estimates of total crop water use.

Grimes & Henderson (1984) demonstrated the variability in crop water use from shallow ground water resulting from the calculation method used for ET_o and crop water use. In one field experiment with alfalfa the ground water contribution ranged from 31 to 45% of the season total depending on the

Table 2. Potential crop water use by cotton from shallow ground water based on Ayars & Hutmacher (1994).

Water quality (dS m^{-1})	Depth (m)	Potential ground water contribution (%)
0.3	1.2	44
7.7	1.2	45
15.4	1.2	39
23.1	1.2	20
30.8	1.2	12
7.7	1.9	26
15.4	1.9	28

method used to calculate ET_o. Wallender et al. (1979) used chloride balance to estimate ground contribution and found that conservative estimates based on ET_o were reliable.

Weighing and drainage lysimeter data are available for a limited number of crops. These data are generally reported as the total contribution for the growing season. This is valuable information but of limited value when trying to operate both irrigation and drainage systems to maximize crop water use. The temporal distribution of crop water use from shallow ground water is also needed to maximize the ground water as a resource and this is generally not available. Ayars & Hutmacher (1994) reported this data as a function of growing degree days and a modified crop coefficient. Grimes & Henderson (1984) reported the cumulative ground water contributions to cotton and seed alfalfa over a two year period as a function of day of the year.

The maximum potential ground water use can be estimated for cotton from Ayars & Hutmacher (1994) study by integrating the area under the base crop coefficient curve and the modified crop coefficient curves and subtracting the value from modified curve from value for the base curve. The difference is divided by the base area to give a percentage. For the modified curves in Figure 3, the potential contribution for cotton is given in Table 2 as a function of ground water quality and depth to water table.

A similar calculation for tomato resulted in a contribution of 30 to 45% with a water table at a depth of 1.2 m and ground water with an EC of 0.3 to 5dS m^{-1}. At the same depth when the ground water EC increased to 7.5 dS m^{-1} the contribution reduced to 20 to 30% and with an EC of 10 dS m^{-1} the contribution reduced to 10%.

Additional research is needed to quantify the temporal distribution of crop water use from shallow ground water for use in irrigation scheduling for a wide variety of crops.

Factors affecting use from shallow ground water

Depth to water table, ground water salinity, crop salt tolerance and age, irrigation management, irrigation water quality, and soil type have all been identified as factors which affect crop water use from shallow ground water. Grimes & Henderson (1984) quantified the volume of water used by alfalfa and cotton in field studies as a function of the depth to ground water and ground water salinity. They found that the percentage water table contribution was a function of both the depth to the water table and the salinity of the ground water. The maximum percentage contribution for a given ground water salinity occurred for increasing depths to the ground water as the ground water salinity increased. The percentage contribution declined as the ground water became more saline and as the depth to water increased for all water qualities. The percentage contribution also decreased as the water table got closer to the soil surface. Reduced aeration and poor root development were suggested as the causes for poor water use with shallow ground water.

Ayars & Hutmacher (1994) demonstrated that increasing depth to ground water and increasing ground water salinity reduced the total uptake from shallow ground water for cotton and tomato. Kruse (1985) found that the ground water contribution to the crop water requirement for corn was affected more by depth to ground water than salinity.

Ayars & Hutmacher's data (1994) indicated that the Maas-Hoffman threshold values for crop yield reduction due to salinization was a good indicator for estimating suitability for crop water use from shallow ground water. They found that crops would use water with an EC of approximately twice the Maas-Hoffman (M-H) threshold value at the same rate as a good (EC $<$ 0.5 dS m^{-1}) water. This provides a quick method for estimating the potential of site for development a shallow ground water management project. If the ground water salinity is less than twice the M-H threshold value for the crops to be grown in the area there is potential for significant use if the water table can be maintained at a level which is accessible to the plant.

Dugas et al. (1990) demonstrated that soils with either high percentages of clay or having a compacted layer have lower levels of ground water uptake. In both cases the reduced hydraulic conductivity limited the transport of water to the root zone and total uptake.

Irrigation frequency and the timing of irrigation are not well researched or defined in the operation of an integrated system. The irrigation interval has to be such that the plant will preferentially begin to use water from ground water instead of stored soil water. This occurs when the soil water potential is low, a condition created by reducing stored soil water. The question then is how much water to apply to maintain a condition where both soil water and ground water will be used. Irrigation with surface methods on an infrequent basis seems to be the most effective method to achieve this result. This means that most of the water will be used from the ground water just prior to the next irrigation and after irrigation has ended. For drip irrigation to be successful, the crop will have to be consistently under irrigated after the soil water content in the root zone has been reduced.

Additional research is needed in the area of maximizing the utilization of ground water as a function of the type of irrigation system and its management with respect to the depth of application, and the soil water content at irrigation.

Managing irrigation and drainage systems

The field studies demonstrated that it is possible to control the irrigation timing using plant based measurements or modified crop coefficients to increase the crop water use from shallow ground water. Control of the water table position is also needed to maximize potential crop water use. Maximum potential use will be achieved when all the proposed methods are included into one management system. The field studies described have implemented a portion of the total management system but not all aspects in a single instance.

The San Joaquin Valley Drainage Program report (1990) stated that using saline drainage water for irrigation of salt tolerant crops is one of the recommended options for drainage water disposal. This leads to the question: how does shallow ground water management compare to using drainage water for supplemental irrigation as a means of disposal?

Data from the case studies can be used to partially answer that question. In the Murrieta project with free flowing drains, it was estimated that an average of 167 mm, 43 mm, and 74 mm of water was used from the ground water by cotton over a three year period. In the Britz project which used the modified crop coefficient to control the operation of the drip system the water use by cotton was estimated to be 270 and 304 mm from shallow ground water without operational drains. This compares to 336 to 573 mm of drainage water used at Murrieta to irrigate cotton as the principal irrigation water source after germination.

Data from each of the field studies indicate that the maximum potential contribution for cotton will occur when the ground water is controlled to a depth of approximately 1.2 m in a silty clay loam soil. *In situ* use of ground water will never equal the amount used as irrigation water because the time the water is available is limited by the plant development. When drainage water is used for irrigation it can be applied over the entire growing season after plant emergence. Significant use by a crop does not occur until the root system is well developed and in the proximity of the water table. This is demonstrated by the modified crop coefficient for cotton when significant extraction from ground water did not occur until the modified crop coefficient curves diverge from the base curve, and this does not happen until approximately 500 growing degree days have accumulated. This can be seen in Figure 3. As the water becomes more saline and the depth to ground water increases, more growth is required before the curves diverge, meaning less water is extracted.

These studies show that there is significant potential for *in situ* use of ground water as both a supplement to irrigation and as a method to reduce drain water disposal. Additional research is needed on the combined management of the irrigation and drainage systems for a wider range of crops and drainage system designs.

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